



Wuppertal Institute
for Climate, Environment
and Energy

**Martin Weiss, Juliane Haufe, Michael Carus,
Miguel Brandão, Stefan Bringezu, Barbara Hermann,
Martin K. Patel**

Review of the Environmental Impacts of Biobased Materials

This is the accepted version of the following article:

Martin Weiss, Juliane Haufe, Michael Carus, Miguel Brandão, Stefan Bringezu,
Barbara Hermann, Martin K. Patel (2012):
Review of the Environmental Impacts of Biobased Materials
In: Journal of Industrial Ecology, vol. 16, no. S1, S169-S181

which has been published in final form at
<http://dx.doi.org/10.1111/j.1530-9290.2012.00468.x>

**Martin Weiss ^{a,*}, Juliane Haufe, Michael Carus ^b,
Miguel Brandão ^a, Stefan Bringezu ^c,
Barbara Hermann ^d, Martin K. Patel ^e**

Review of the Environmental Impacts of Biobased Materials

^a European Commission – DG Joint Research Centre, Italy

^b nova-Institut GmbH, Hürth, Germany

^c Wuppertal Institute for Climate, Environment and Energy, Wuppertal, Germany

^d PepsiCo International Limited R&D, Leicester, UK

^e Utrecht University, Utrecht, The Netherlands

* Corresponding author: Martin Weiss, European Commission – DG Joint Research Centre,
Institute for Energy and Transport – Sustainable Transport Unit, Via Enrico Fermi 2749
TP 230, 21010 Ispra, Italy

E-mail: martin.weiss@jrc.ec.europa.eu

Phone: 0039-0332-78-5965

A review of life cycle assessment studies on bio-based materials

Martin Weiss, Juliane Haufe, Michael Carus, Miguel Brandão, Stefan Bringezu,
Barbara Hermann, and Martin K. Patel

Abstract

Concerns over climate change and the security of industrial feedstock supply have been opening a growing market for bio-based materials. However, this development confronts scientists, policy-makers, and industry with a challenge because the production of bio-based materials requires land and is typically associated with the application of agrochemicals. This article addresses the environmental impacts of bio-based materials in a meta-analysis of 44 Life Cycle Assessment (LCA) studies. We find that one metric ton (t) of bio-based materials saves relative to conventional materials 55 ± 34 GJ primary energy and 3 ± 1 t CO₂-equivalents of greenhouse gases. However, one metric ton of bio-based materials may increase eutrophication by 5 ± 7 kg phosphate-equivalents and stratospheric ozone depletion by 1.9 ± 1.8 kg nitrous oxide-equivalents. Our results are inconclusive with regard to acidification (savings of 2 ± 20 kg sulphur dioxide-equivalents/t of bio-based materials) and photochemical ozone formation (savings of 0.3 ± 2.4 kg ethene-equivalents/t of bio-based materials). The large variability in the results of individual life cycle assessment studies highlights the difficulties to draw general conclusions about the environmental impacts of bio-based materials. Still, characteristic of most bio-based materials are impacts caused by the application of fertilizers and pesticides during industrial biomass cultivation. Additional land use impacts, such as the potential loss of biodiversity, soil carbon depletion, soil erosion, deforestation, as well as greenhouse-gas emissions from indirect land use change are not quantified in this review. Clearly, these impacts should be considered in a comprehensive environmental evaluation of bio-based materials.

Key words: bio-based materials, Life Cycle Assessment (LCA), environmental impacts, biomass

1 Introduction

Bio-based wood, paper, and textile materials have been produced for centuries. Together, these materials account for 14% of the global bulk materials production, while synthetic materials, predominantly produced from fossil-based feedstock, only account for a share of 7% (own estimates based on Deimling et al. 2007, Lasserre 2008, OGS 2007, UN 2008, Saygin and Patel 2010, IAI 2010)ⁱ. Concerns about greenhouse gas (GHG) emissions and the security of fossil-based feedstock supply, however, have been triggering relatively recent interest in using biomass for the production of synthetic materials (Patel et al. 2006, Deimling et al. 2007, Shen et al. 2009a,b). As of 2008, biomass provided 10% of the feedstock of the European chemical industry (Rothermel 2008). The production of bio-based synthetic materials such as polymers, lubricants, and fibers has been growing continuously in the past decade. Bio-based polymers such as alkyd resins or polylactic acid accounted for 7% of the total polymer production (PlasticsEurope 2007) while bio-based plastics (comprising polymers with a molecular mass higher than 20,000 unified atomic mass units) are still in their infancy. By the end of 2007 they account for only 0.3% (0.36 Mt) of the worldwide plastics production (Shen et al. 2009a,b).

Technological innovation will likely continue to open a wide range of new applications for bio-based materials, including the use of bio-based plastics for consumer goods and engineering purposes, of composites in the automotive industry, or of novel insulation and packaging materials (Hermann et al. 2010a, Shen et al. 2008, 2009a). Breakthroughs can be expected in the coming years for integrated biorefineries, which may optimize the use of biomass by providing a whole range of materials and energy products from bio-based feedstock.

However, the prospects for novel bio-based materials present scientists, policy-makers, and industry with an environmental challenge: the benefits of replacing fossil-based feedstock and reducing GHG emissions may come at the cost of additional land use and related environmental impacts. Strategic decision-making thus requires a thorough analysis of the environmental impacts of bio-based materials in comparison to their conventional fossil-based or mineral-based counterparts. To this end, Life Cycle Assessment (LCA) has been applied to a large range of bio-based materials, including starch-based polymers (e.g., Dinkel et al. 1996, Würdinger et al. 2002, Patel et al. 2006), fiber-composites (e.g., Wötzel et al. 1999, Müller-Sämann et al. 2002, Zah et al. 2007), or hydraulic oils and lubricants (e.g., Reinhardt et al. 2001). Detailed reviews of the LCA literature have focused initially on non-renewable energy use and GHG emissions only (e.g., Dornburg et al. 2004, Kaenzig et al. 2004), whereas more recent reviews also include additional environmental impact categories such as eutrophication and acidification (e.g., Deimling et al. 2007, Oertel 2007, Weiss et al. 2007). A more comprehensive quantification of the environmental impacts associated with a large range of bio-based materials is, however, still missing. Here, we address this problem by presenting a meta-analysis that summarizes the results of the existing LCA literature on bio-based materials. We do not claim absolute completeness with respect to all published LCA studies. Instead, we seek to: (i) identify general patterns in the environmental impacts of a wide range of bio-based materials and (ii) discuss potentials for making the production, consumption, and disposal of bio-based materials more environmentally friendly. This article excludes technical, economic, and social aspects of bio-based materials (e.g., production costs or the impact of non-food biomass farming on food prices and the livelihood of smallholders in the tropics). However, these aspects should be considered in a comprehensive evaluation of bio-based materials. The article continues by presenting background information and our methodology for reviewing the LCA literature on bio-based materials. We then present results, discuss uncertainties and critical aspects, and identify options for reducing the environmental impacts of bio-based materials.

2 Background information and methodology

Bio-based materials comprise materials that are produced partially or entirely from biomass, i.e., from terrestrial and marine plants, parts thereof, as well as biogenic residues and waste. Bio-based materials include traditional wood, paper, and textile materials as well as novel bio-based plastics, resins, lubricants, composites, pharmaceuticals, and cosmetics. The manufacturing processes of bio-based materials range from extraction and simple mechanical processing of natural fibers to fermentation and advanced enzymatic or catalytic conversions.

The environmental impacts of bio-based as well as conventional fossil-based or mineral-based materials are typically quantified through the internationally standardized LCA methodology (ISO 2006a,b). Here, we review the LCA literature on bio-based materials by applying: (i) a standard internet search for peer-reviewed articles contained in the online databases 'Web of Science' and 'Scopus' as well as (ii) a Google-based search for scientific and governmental reports, workshop documents, and working papers. We include LCA studies in our meta-analysis if they provide a minimum of methodological background information, quantify the environmental impacts of bio-based materials in physical units for at least one impact category, and are published in the English and German languages before December 2011. LCA results presented in flyers or oral presentations are excluded from this review. Likewise, we exclude LCA studies that report environmental impacts in percentages or indices only (e.g., Gironi and Piemonte 2011, Guo et al. 2011). This approach does not allow a complete coverage of all relevant LCA studies published to date; still, it is suitable for identifying the general pattern in the environmental impacts of bio-based materials.

We include in our review a total of 44 LCA studies that cover around 60 individual bio-based materials and 350 different life cycle scenarios (see Tables A1 and A3 in the Appendix). Preliminary scanning through the literature reveals that most studies focus on bio-based materials of European origin being manufactured by both small pilot installations and large-scale industrial plants. The reviewed LCA

studies generally differ from each other in many, if not all, assumptions and choices made regarding, e.g., system boundaries, functional units, life cycle scenarios, or allocation procedures as well as in the detail of explanations on methodology and results. We refrain from correcting for differences in choices and assumptions. This approach is justified given the scope of this meta-analysis and the generally limited availability of necessary background information and inventory data.

Individual LCA studies may also differ from each other with in the method chosen for aggregating inventory data into individual environmental impact categories. The commonly used methods have been described by Heijungs et al. (1992), UBA (1995), and Guinée (2001). Our review covers the environmental impacts of bio-based materials in six categories, which we characterize and quantify as follows (Guinée 2001):

- (i) non-renewable energy use (NREU), quantified in gigajoules [GJ]
- (ii) climate change, quantified in metric tons of carbon dioxide equivalents [t CO₂-equ.] by considering the global warming potential of GHG emissions over a time horizon of 100 years
- (iii) eutrophication, quantified in kilograms of phosphate equivalents [kg PO₄-equ.]
- (iv) acidification, quantified in kilograms of sulfate equivalents [kg SO₂-equ.]
- (v) stratospheric ozone depletion, quantified in kilograms of dinitrogen oxide equivalents [kg N₂O-equ.]
- (vi) photochemical ozone formation, quantified in kilograms of ethane equivalents [kg ethene-equ.]

We express the relative environmental impacts of bio-based materials in comparison to the environmental impacts of conventional materials as:

$$D_{ij} = EI_{bio-based,ij} - EI_{fossil-based,ij}$$

where: D_{ij} = the difference in the environmental impact of the bio-based and conventional material

$EI_{bio-based,ij}$ = the environmental impact of the bio-based material

$EI_{fossil-based,ij}$ = the environmental impact of the conventional material

i = the specific material

j = the specific environmental impact category

This approach follows the methodology applied in most of the reviewed LCA studies and results in negative values if bio-based materials exert lower impacts on the environment than their conventional counterparts. We quantify the relative environmental impacts of bio-based materials per metric ton of product [t^{-1}] and per hectare of agricultural land and year [$(ha \cdot a)^{-1}$]. Several LCA studies report their results in terms of alternative functional units (e.g., Madival et al. 2009, Hermann et al. 2010a). We include these studies in our meta-analysis and recalculate the environmental impacts based on the background information provided in each respective study. If the information in the respective LCA studies is insufficient for estimating the relative environmental impacts of bio-based materials, we use information from additional literature sources in the following manner (see also Table A1 in the Appendix):

- (i) A few LCA studies on plastics present the environmental impacts of the bio-based materials but refrain from comparing these with the impacts of fossil-based counterparts (e.g., Vink et al. 2007). In these cases, we calculate the difference in the impacts of bio-based and fossil-based materials based on data provided for fossil-based plastics by Boustead (2005a-d).
- (ii) The reviewed LCA studies typically express the environmental impacts of bio-based and conventional materials by using product-based functional units (e.g., one metric ton or a square meter of material). To express the findings of part of these studies also in terms of a land use-based functional unit (i.e., per hectare and year), we include in our meta-analysis the results of

two earlier recalculations conducted by the authors (Weiss and Patel 2007; Haufe 2010).

This method does not allow identifying the land use-specific impacts of all material cases investigated in the reviewed LCA studies. Still, our approach is justified by the research objective because it allows a more complete insight into the relative environmental impacts of bio-based materials than the sole comparison of the results presented in the LCA studies.

We estimate stratospheric ozone depletion based on nitrous oxide (N₂O) emissions only and exclude chlorofluorocarbons that are of minor importance since their banning by the Montreal Protocol in 1994 (Würdinger et al 2002; Müller-Sämann et al. 2002). We present the results in each impact category disaggregated for nine individual groups of bio-based materials and as total over all materials. We report the arithmetic mean and the standard deviation of the environmental impacts as identified in the reviewed LCA studies for each group of bio-based materials. The standard deviation can be regarded as indicative of the uncertainty interval in our results and reflects, to some extent, the diversity of life-cycle scenarios and methodological choices made in the reviewed LCA studies. We calculate the overall average impact of bio-based materials in each impact category based on the mean environmental impacts of the individual groups of bio-based materials (see Table A1 in the Appendix). This way, we ensure an equal representation of all nine groups of materials in the overall average.

We put our results in perspective by normalizing the overall average environmental impacts of bio-based materials based on the worldwide average inhabitant-equivalent values for the year 2000 with regards to primary energy consumption (EIA 2011) and the five environmental impact categories (Sleeswijk et al. 2008) covered here. This approach allows comparing our results with the worldwide average environmental impacts of one person in the year 2000. We discuss additional environmental impacts and secondary effects of bio-based materials

alongside the uncertainties of our review in semi-quantitative terms after presenting the results.

3 Results

Non-renewable energy use and climate change

We find that bio-based materials save, on average, 55 ± 34 GJ/t and 127 ± 79 GJ/(ha*a) of non-renewable energy. These savings exceed the worldwide average per capita primary energy consumption in the year 2000 by a factor 8 ± 5 and 18 ± 11 , respectively, of. Furthermore, bio-based materials save, on average, 3 ± 1 t CO₂-eq./t and 8 ± 5 t CO₂-eq./ha*a) of GHG emissions relative to conventional product alternatives (Figure 1 and Table A2 in the Appendix), being equivalent to $37 \pm 21\%$ and $111 \pm 79\%$, respectively of the worldwide average per capita GHG emissions in the year 2000. The results vary, however, within large ranges. This makes it infeasible to identify individual groups of bio-based materials which are environmentally superior with respect to non-renewable energy use and climate change.

Special attention has been paid in recent years to the production of bio-based chemicals. Patel et al. (2006) conducted an extensive *cradle-to-factory gate* (C-FG) analysis on the non-renewable primary energy use and the GHG emissions of a wide range of bio-based chemicals (Figure 2 and Table A3 in the Appendix). The findings of Patel et al. (2006) are in line with our results for a larger range of bio-based materials, indicating that the production of bio-based chemicals saves, on average, 43 ± 27 GJ/t and reduces the GHG emissions by 3 ± 2 t CO₂-eq./t in comparison to conventional fossil-based chemicals. The variability in the results for individual bio-based chemicals partially stems from differing assumptions regarding the type of biomass feedstock (i.e., corn starch, lignocellulosic biomass, or sucrose from sugar cane) and the applied production technology (e.g., current versus future technologies; aerobic versus anaerobic processes, or continuous versus batch processes).

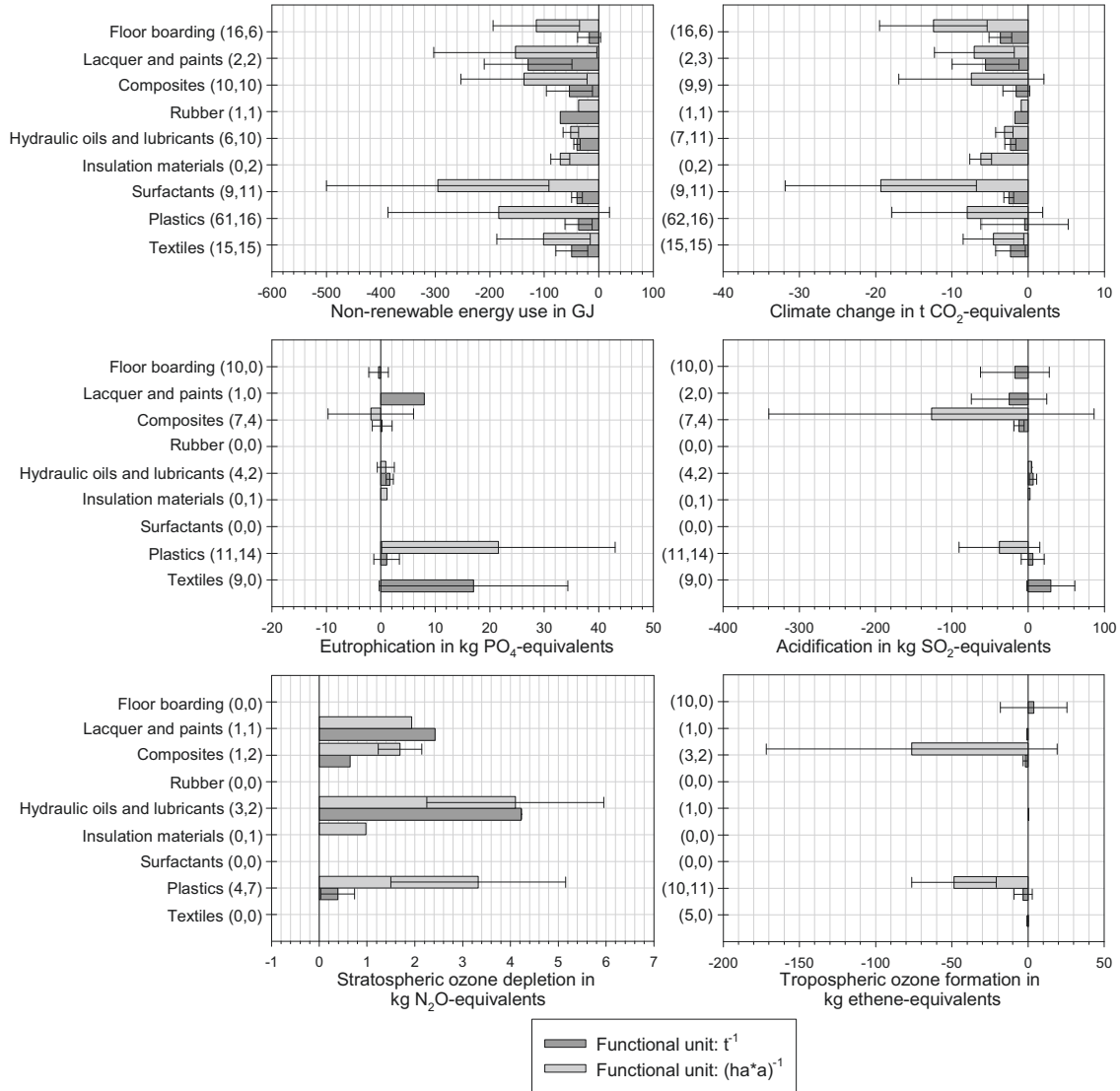


Figure 1: Product-specific environmental impacts of bio-based materials in comparison to conventional product alternatives (D_{ij}); uncertainty intervals represent the standard deviation of data; numbers in parentheses indicate the sample size for the functional units of per metric ton and per hectare and year, respectively

Further support of these findings is provided by Ren and Patel (2009), who estimate that using biomass feedstock for the production of basic chemicals such as ethylene, propylene, and aromatics saves 6 ± 5 t CO₂/t and 11 ± 6 t CO₂/t compared to the use of methane and coal feedstock, respectively. The GHG emission savings identified so

far disregard, however, the potentially substantial effects of indirect land use change (see Discussion section).

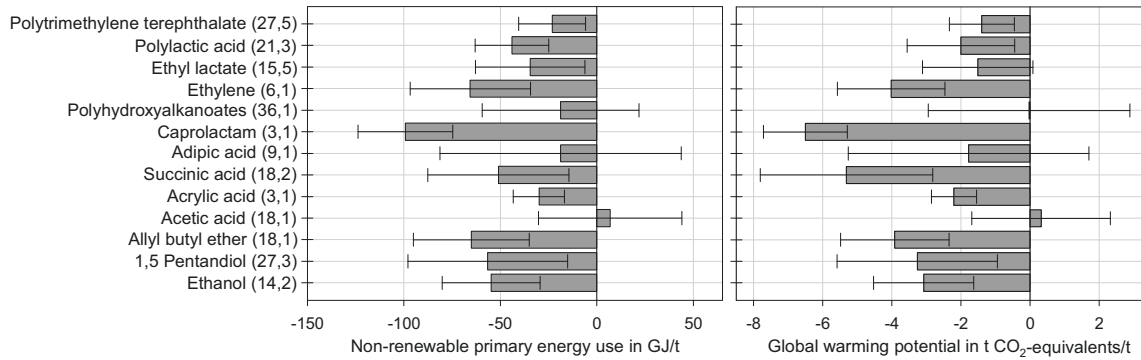


Figure 2: Non-renewable primary energy use and GHG emissions of bio-based chemicals in comparison to conventional product alternatives (D_{ij}); uncertainty intervals represent the standard deviation of data; numbers in parentheses indicate the sample size for the bio-based and the conventional material, respectively (Data source: Patel et al. 2006)

Eutrophication and acidification

The environmental benefits of bio-based materials in the categories of non-renewable primary energy use and GHG emissions are likely associated with environmental burdens regarding environmental eutrophication (Figure 1). Bio-based materials may induce, on average, 5 ± 7 kg PO₄-eq./t and 6 ± 11 kg PO₄-eq./ha*a higher emissions on the environment than their conventional counterparts. The additional impacts thereby account for $66 \pm 98\%$ and $79 \pm 157\%$, respectively of the worldwide average per capita fresh water eutrophication in the year 2000. Our results can be explained with the high eutrophication potential of biomass production with industrial farming practices, and more specifically, with the nitrate and phosphate leaching from the applied nitrogen fertilizers as well as with the ammonia emissions from manure applications (e.g., Würdinger et al. 2002, Deimling et al. 2007, Cherubini and Jungmeier 2010).

Our findings are inconclusive with respect to acidification, indicating average savings of bio-based materials relative to conventional materials of 2 ± 20 kg sulfate SO_2 -eq./t and 39 ± 61 kg SO_2 -eq./($\text{ha} \cdot \text{a}$). This result translates into a factor of 0.3 ± 2.9 and 5.7 ± 8.9 , respectively of the worldwide average per capita acidification in the year 2000. The relatively large uncertainty intervals indicate that acidification is largely case specific. Bio-based plastics and composites, for example, seem to decrease acidification, whereas bio-based lubricants are likely to increase acidification relative to their conventional counterparts (e.g., Reinhardt et al. 2001, Müller-Sämann et al. 2002). Acidification is mainly caused by emissions from the application of manure and mineral fertilizers in agriculture, as well as from combustion processes. The first source is relevant for biomass production in general, the second one predominantly for lubricants. Even if bio-based materials are incinerated at the end of their life cycle, the resulting emissions may constitute only a minor portion of the total acidifying emissions along the relatively long product life cycle.

Stratospheric ozone depletion and photochemical ozone formation

A relatively limited number of seven LCA studies indicates that bio-based materials may increase stratospheric ozone depletion by, on average, 1.9 ± 1.8 kg N_2O -eq./t and 2.4 ± 1.3 kg N_2O -eq./($\text{ha} \cdot \text{a}$) relative to their conventional counterparts (Figure 1). The additional impacts thereby account for $28 \pm 26\%$ and $35 \pm 18\%$, respectively of the worldwide average per capita ozone depletion potential in the year 2000. The impacts in this category largely result from the N_2O emissions that originate from fertilizer application in agriculture (Müller-Sämann et al. 2002, Würdinger et al. 2002). Since fertilizer application is characteristic for industrial farming practices that are typically used for growing biomass feedstock, high stratospheric ozone depletion potentials may be found for a wide range of bio-based materials.

Our findings are largely inconclusive with respect to photochemical ozone formation, indicating that bio-based materials may save, on average, 0.3 ± 2.4 kg ethene-eq./t and 62 ± 20 kg ethene-eq./($\text{ha} \cdot \text{a}$) as compared with conventional

materials (Figure 1). These savings account for $5 \pm 35\%$ and a factor of 9 ± 3 , respectively of the worldwide average ozone formation potential in the year 2000. The large deviation between the product-based and land use-based results as well as the relatively large uncertainty intervals warrant caution and suggest that impacts in this category are case specific. The substantial deviations in the relative magnitude of the uncertainty intervals results here because different LCA studies compose the two data samples that are used to calculate the product-specific and land use-specific ozone formation potential. More specifically, the land use-based analysis does not contain LCA studies on floor boarding, a group of materials that shows a high variability in its impacts on photochemical ozone formation. Typically, floor boarding shows a high ozone formation potential in comparison to other bio-based materials. This observation stems from volatile organic compounds that are emitted from solvents contained in the glues and surface finishing of parquet floors. Gluing and surface finishing together account for 95% of the ozone formation potentials of parquet (Nebel et al. 2006). However, solid floor boards that are fixed mechanically without the application of glues show substantially lower solvent emissions than the over floor boarding scenarios (Nebel et al. 2006). Both parquet floors and solid floor boarding are included in the analysis, thus causing a large variability in the product-specific photochemical ozone formation potentials of floor boarding.

Additional environmental impacts

In addition to these results, bio-based materials exert a large variety of environmental impacts that are not quantified by most LCA studies and thus by this review. Several LCA studies suggest that bio-based materials may:

- (i) exert lower human and terrestrial ecotoxicity as well as carcinogenic potentials than conventional materials (e.g., Wötzl et al. 1999, Corbière-Nicollier et al. 2001; Würdinger et al. 2002; Harding et al. 2007, Shen and Patel 2010)
- (ii) exert higher aquatic ecotoxicity than conventional materials (Shen and Patel 2010)

Additional land use-related impacts, such as water consumption for biomass cultivation, soil erosion, soil carbon losses, and changes in biodiversity, have received recent attention (see, e.g., Geyer et al. 2010a,b). These impacts are particularly relevant at the local and regional scales, but are difficult to quantify and are therefore excluded from both the majority of LCA studies and this review.

4 Discussion

Our review indicates that bio-based materials on average save non-renewable energy and can help to mitigate climate change (if indirect land use change is disregarded, see discussion below). These findings confirm the results of previous LCA reviews that are, however, based on smaller data samples (Deimling et al. 2007, Oertel 2007, Patel et al. 2003, Dornburg et al. 2004, Kaenzig et al. 2004, Weiss et al. 2007). The LCA literature suggests that bio-based materials, on average, are associated with higher eutrophication and stratospheric ozone depletion than conventional materials. Our findings are inconclusive with regard to acidification and photochemical ozone formation. A similar tendency in the environmental impacts has also been identified by the LCA literature on bioenergy and biofuels (e.g., Reinhardt et al. 2000, Quirin et al. 2004, Larson 2006, von Blottnitz and Curran 2007, WBGU 2008, Schmitz et al. 2009). The relative environmental impacts of bio-based materials scatter over a wide range, spanning over both negative and positive values for several impact categories (Figures 1 and Table A1 in the Appendix). Decision making should account for this variability by considering individual cases, potentially weighing global environmental concerns (e.g., climate change, stratospheric ozone depletion) against local and regional concerns (e.g., eutrophication, photochemical ozone formation, land use change).

4.1 Discussion of uncertainties

The results of our review are subject to uncertainties and limitations that arise from (i) the method used for analyzing the LCA studies and (ii) the uncertainty in the

inventory data as well as the diversity of methodological choices applied in the individual LCA studies.

Addressing the first source of uncertainty, our review only quantifies the environmental impact of bio-based materials in six categories. These categories are typically the most prominent ones addressed in the LCA literature. Still, they enable only a partial evaluation of bio-based materials because of insufficient accounting for: (i) other relevant land use-related impacts as well as (ii) the potential risks resulting from the use of genetically-modified crops and microorganisms.

Our approach to refrain from harmonizing the reviewed LCA studies with respect to differences in methodological choices and inventory data may limit the reliability and accuracy of our results. Methodological differences are likely to result in a random error for impact categories of sufficiently large data samples (e.g., non-renewable energy use or GHG emissions). However, more caution is required when interpreting the results for impact categories in which only a few data points are available (e.g., acidification, photochemical ozone formation) because methodological inconsistencies may lead here to systematic errors. In the latter cases, the data samples are often highly skewed, making the mean a less reliable estimator of the general tendency of the sample. To analyze whether the skewness of data samples affects the interpretation of our results, we calculate also the median environmental impacts (see Table A3 in the Appendix). The deviations between the arithmetic mean and median are typically negligible for the totals of all bio-based materials as well as for impact categories and groups of materials for which large data samples are analyzed (e.g., as is the case for non-renewable energy use and GHG emissions). The deviations become, however, larger for cases in which small data samples span large value ranges. Such a case appears for, e.g., the acidification potential of floor boarding where the mean and median may lead to different conclusions (see Table A3). Caution is therefore necessary before drawing conclusions solely based on one indicator for the central tendency of data samples.

Addressing the second source of uncertainty in all rigidity is beyond the scope of this article, given both the vast diversity of plausible methodological choices and the level of detailed information provided by the reviewed LCA studies. Instead, we provide some indication about the uncertainty associated with the results of individual LCA studies.

The data used for the inventory analysis are typically subject to substantial uncertainties. Dinkel et al. (1996) quantify error ranges of inventory data of 40% and deviations resulting from differences in the applied allocation method of up to 90% of the final result. Miller et al. (2007) emphasize the considerable variability and uncertainty in the emission profiles of agricultural systems due to differences in geography, climate, and agricultural practices. The aggregate volatile organic compound and N₂O emissions, for example, vary in their study of soybean-based lubricants by over 300% due to variability in agricultural processes, cropland characteristics, and soybean oil extraction. Furthermore, the reviewed LCA studies often vary from each other in the number of pollutants included in their inventory analysis as well as in their method used for aggregating inventory data into individual environmental impact categories (compare, e.g., Wötzl et al. 1995, Corbière-Nicollier et al. 2001, Müller-Sämann et al. 2003, Turunen and van der Werf 2006). The latter inconsistency might be negligible for our analysis (see, e.g., Corbière-Nicollier et al. 2001, Dreyer et al. 2003). However, the former source of uncertainty leads to a systematic underestimation of environmental impacts. The former sources of uncertainty, however, may present a random error in our review of environmental impact categories and groups of materials for which a large amount of LCA studies is available (e.g., NREU and GHG emissions of plastics or textiles). However, systematic uncertainties may result for the other four, less frequently analyzed, environmental impact categories. Again, one should be cautious when interpreting the results for these categories.

4.2 Discussion of critical aspects in the life cycle assessment of bio-based materials

The large range of results for individual groups of bio-based materials stems from the diversity of product systems, methodological choices, and plausible assumptions made in the reviewed LCAs (see, e.g., Patel et al. 2006). Usually, it is a combination of choices that potentially leads to substantial differences in the outcome of individual LCA studies, even if similar product scenarios are analyzed. Among these choices, the following are particularly critical: (i) the choice of functional unit, (ii) the selection of crops, (iii) the treatment of secondary effects such as impacts of indirect land use change, (iv) the treatment of agricultural residues, (v) the consideration of alternative agricultural practices, (vi) the treatment of temporary carbon storage, and (vii) choices regarding end-of-life waste treatment.

Choice of functional unit

The land use in the production of biomass feedstock can be accounted for by expressing the environmental impacts of bio-based materials per area of cultivated or harvested land $[(\text{ha} \cdot \text{a})^{-1}]$ instead of per unit of product, e.g., $[\text{t}^{-1}]$. This so-called land use-based approach provides an indication for the *land use efficiency* of bio-based materials. The choice of either a land use-based or a product-based approach does not change the sign of the results but affects their magnitude. In particular, materials with a very low share of a bio-based component can potentially achieve very high land use efficiency if the chosen material is environmentally favorable because the specific land requirements are low. Bringezu et al. (2009) therefore recommend that assessments of biomass use should take two perspectives, namely a land use-based and a product-based perspective, and discuss the outcomes in an integrated manner. Further analysis may supplement the discussed approaches by quantifying the *environmental intensity* of bio-based materials, expressed as environmental impact per monetary unit, i.e., the specific price or production costs of bio-based materials. Such an analysis could provide new insights into the environmental cost efficiency of bio-based materials.

Selection of crops

The environmental impacts of bio-based materials depend on the chosen feedstock. Differences result here from crop-specific farming practices, climatic conditions, agricultural yields, transport distances, use of residues for co-products, as well plant-specific yields characterized by, e.g., starch and fiber content. The environmental impacts of bio-based materials typically decrease if crop-specific feedstock yields are high, environmental impacts of agricultural practices are low, and for cases in which agricultural crops yield substantial amounts of useful co-products (e.g., bagasse in the case of sugar cane). In comparison to fossil-based chemicals, using lignocellulosic biomass or sugar cane as a feedstock for the production of bio-based chemicals saves, on average, 60% and 120% more GHG emissions per metric ton, respectively than using corn starch (Patel et al. 2006).

Secondary effects – the case of indirect land use change

The demand of biomass feedstock for producing bio-based materials may expand the agricultural land use and thus accelerate the direct and indirect land use change on a global scale. Indirect land use change, that is, the unintended expansion of farmland elsewhere due to the rededication of existing farmland, may add substantially to the overall environmental impacts of bio-based materials. The effects of indirect land use change are excluded from the reviewed LCA studies but have been studied in the context of biofuels. Plevin et al. (2010) found that the GHG emissions from indirect land use change of corn ethanol production in the US span between 10 and 340 kg CO₂-eq./GJ ethanol, thereby ranging from small to several times greater than the life cycle emissions of gasoline. Substantial indirect land use change effects for the biofuels production in the USA and in Brazil have been identified by Searchinger et al. (2010), Lapola et al. (2010), and Arima et al. (2011).

On a related note, the effects of direct land use have been analyzed by Piemonte and Gironi (2010), who find that land use emissions have a substantial and largely negative impact on the GHG emission savings of bioplastics unless waste biomass or biomass grown on degraded or abandoned land is used as feedstock. Wicke et al.

(2008) find that direct land use change is the most decisive factor in the GHG emissions of palm oil energy chains. Hoefnagels et al. (2010) show that the GHG emissions directly associated with the production of biodiesel from palm oil quadruple if plantations are located on former peat lands and rainforests instead of on degraded land or logged-over forests. Based on these considerations it is reasonable to assume that indirect land use change will reduce the GHG emission savings of bio-based materials; the extent to which this will happen is, however, uncertain and subject of ongoing research. In general, the impacts of land use change can be reduced by:

- (i) producing non-food biomass on degraded land that will need to be restored,
- (ii) achieving yield and productivity increases in regions with lagging yield developments, such as Sub-Sahara Africa (Bruinsma 2009, Nellemann et al. 2009, Hubert et al. 2010),
- (iii) more intensive use of farmland by planting so-called *agricultural intercrops* between main cropping periods, which serve energy or material purposes (Karpenstein-Machan 2001),
- (iii) introducing comprehensive land use management guidelines,
- (iv) establishing programs and policies of sustainable resource management, which also consider and limit the consumption of global resources, including global land use (Bringezu and Bleischwitz 2009).

Treatment of agricultural residues

Often, only parts of crops are used in the production of bio-based materials, leaving residues available for other purposes. The LCAs generally assume that residues either remain on the field as a substitute for mineral fertilizers (e.g., Würdinger et al. 2002) or are simply excluded from the product system (e.g., Corbière-Nicollier et al. 2001). The environmental impacts of bio-based materials may, however, substantially decline if residues are used for materials or other useful purposes. Dornburg et al. (2004) identified reductions in the non-renewable energy use and GHG emissions of bio-based polymers of up to 190 GJ and 15 t CO₂ per hectare and

year, respectively, if agricultural residues are used for energy. Similar effects can be expected if agricultural and forestry residues or biogenic wastes are utilized for the production of bio-based materials and second-generation biofuels in integrated biorefineries (Williams et al. 2009; Cherubini and Jungmeier 2010). Such integrated biorefineries present a promising technological solution to make use of the whole crop and subsequently reduce the environmental impacts associated with the production of bio-based materials, energy, and fuels.

Agricultural practices

The relatively high environmental impacts of bio-based materials in the categories of eutrophication and stratospheric ozone depletion (but also a substantial share of their non-energy use and GHG emissions) arise from biomass production with conventional industrial farming practices. Kim and Dale (2008) found that no-tillage farming and the cultivation of winter crops can decrease the environmental impacts of corn production by up to 70%. Würdinger et al. (2002) have demonstrated that extensive farming practices, which differs from conventional farming in that they apply no synthetic pesticides and nitrogen fertilizers, substantially reduce the eutrophication, acidification, and stratospheric ozone depletion potential of bio-based starch-based loose-fill packaging materials. In particular, the product-related N₂O emissions can be decreased by 95% if wheat for the production of loose-fills is extensively grown (Figure 3; Würdinger et al. 2002).

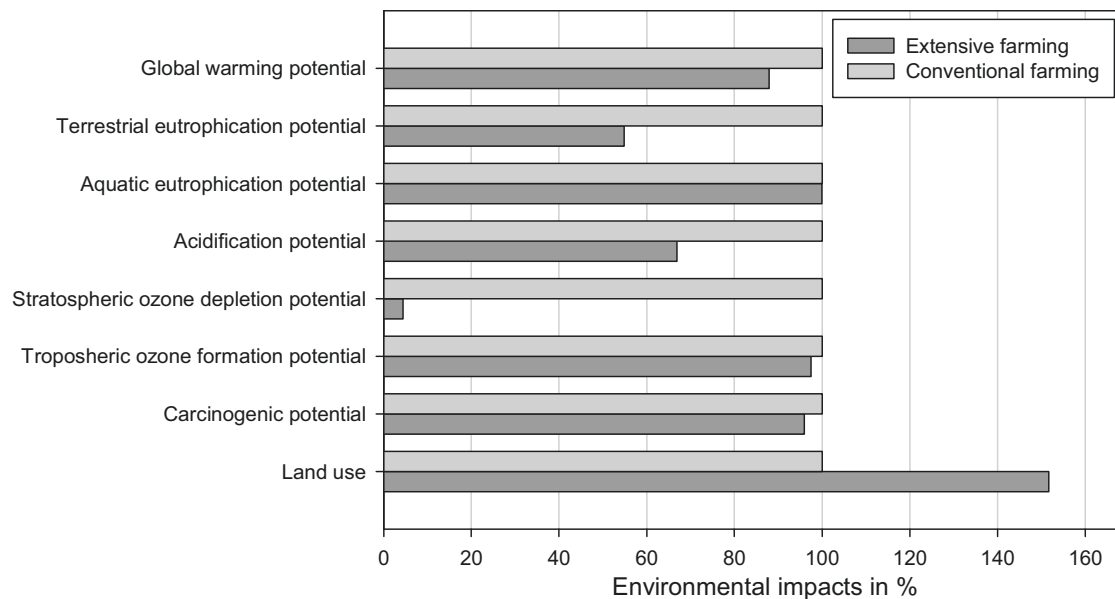


Figure 3: The relative environmental impacts of a defined volume of loose-fill packaging materials produced from conventional and extensively grown wheat-starch (Data source: Würdinger et al. 2002)

Since the restriction of ozone-depleting substances under the Montreal Protocol (UNEP 2000), fertilizer induced N_2O emissions have been constituting the single most important driver of stratospheric ozone depletion on a global scale (Ravishankara et al. 2009). Nitrous oxide is furthermore a potent greenhouse gas that might not always be accounted for appropriately in the assessment of GHG emissions from farming (Bringezu et al. 2009). Smeets et al. (2009) suggest that N_2O emissions might contribute 10-80% to the total GHG emissions of biofuels, depending on crop type, climate conditions, and reference land use scenario. Results for biofuels indicate that altogether 3-5% of the provided nitrogen might be converted to N_2O (Crutzen et al. 2007). Although contested (see, e.g., Ogle et al. 2008, Smeets et al. 2009), this finding suggests that the commonly used average emission factor of 1% (IPCC 2006) may substantially underestimate the actual N_2O emissions. Optimized farming practices and crop management, which includes avoiding stagnant anaerobic soil conditions, have to be adopted to substantially reduce N_2O emissions. However, as changes are generally constrained by prevailing economic and social factors, it remains doubtful as to whether substantial

reductions in the environmental impacts of biomass production are achievable on a large scale. The findings of Würdinger et al. (2002) furthermore indicate that extensive farming practices may come at the cost of decreasing yields and thus higher land requirements for biomass production. The expansion of extensive farming might thus increase the environmental impacts of direct and indirect land use change. This complexity requires a thorough evaluation of bio-based materials on regional, national, and global scales.

Treatment of temporary carbon storage

When assessing the GHG emissions of bio-based materials, there are three ways of addressing bio-based carbon:

- (i) ignoring it by considering bio-based carbon as neutral because it has been withdrawn from the atmosphere and will be returned to the atmosphere within a limited period of time; this approach implies that any allocation issue that may arise is implicitly treated through the relative carbon content of co-products (Guinée et al. 2009);
- (ii) considering it by regarding bio-based carbon to be neutral but, as opposed to the previous option, allocation of bio-based carbon can be treated consistently with the allocation of other environmental burdens,
- (iii) crediting it by considering bio-based carbon to be sequestered in bio-based materials; this approach is more relevant for consequential LCAs, where the consideration of reference land uses is critical (Brandão and Levasseur, 2011).

Crediting additional carbon storage implies that both the uptake of carbon from the atmosphere (that is temporarily contained in bio-based materials), as well as its release during use or waste treatment, must be accounted for as positive or negative GHG emissions. This approach regards the time period in which the carbon is stored outside of the atmosphere as beneficial for the climate due to the temporarily foregone radiative forcing. As a consequence, it may lead to systematically lower

GHG emissions for a cradle-to-factory gate analysis than for a cradle-to-grave analysis.

End-of-life waste treatment

Covering the end-of-life waste treatment phase allows for analyzing the impacts of a variety of waste treatment scenarios that may be associated with a wide range of GHG emissions. By including the end-of-life waste treatment, an LCA can, in particular, investigate whether biodegradability is indeed an environmentally favorable property of bio-based materials (Würdinger et al. 2002, Groot and Borén 2010, Hermann et al. 2010b). Hermann et al. (2010b) show for polylactic acid that the product-specific GHG emissions might vary by approximately 20% depending on whether or not energy is recovered during waste incineration. In the LCA study of loose-fills, Würdinger et al. (2002) suggest that the differences in GHG emissions between various waste treatment scenarios are similar to the differences between bio-based and fossil-based loose-fill packaging materials. These findings call for a detailed assessment of all major waste management options including landfilling, composting, waste-to-energy facilities, municipal waste incineration, digestion, and recycling (Edelmann and Schleiss 2001, Amlinger et al. 2008). Carbon cascading by using biomass first for material purposes and then recovering energy through incineration at the end of the product life cycle can maximize the GHG emission savings of bio-based materials (Dornburg et al. 2009; Oertel 2007, Bringezu et al. 2009). However, recent LCA studies have shown that composting can be more attractive than incineration (thus carbon cascading) if compost is used to replenish carbon stocks in agricultural soils (Hermann et al. 2010b, Khoo and Tan 2010). The results of LCA studies remain ambiguous and suggest that the GHG emission savings achievable for bio-based materials via carbon cascading, i.e., incineration with energy recovery and biodegradation, i.e., composting are case specific.

5 Conclusions and outlook

The findings of this meta-analysis allow us to draw the following conclusions:

- Bio-based materials save non-renewable energy resources, thus enable the manufacturing industry to substitute renewable resources for part of its fossil-based or mineral-based feedstock.
- Bio-based materials generally exert lower environmental impacts than their conventional counterparts in the categories of climate change (if GHG emissions from indirect land use change are neglected).
- Bio-based materials may generally exert higher environmental impacts than their conventional counterparts in the categories of eutrophication and stratospheric ozone depletion; the results are inconclusive with regard to acidification and photochemical ozone formation.
- Normalizing our results based on worldwide average inhabitant-equivalent values suggests that bio-based materials may contribute more substantially to non-renewable energy savings than they might decrease or increase impacts in the other environmental impact categories covered here.
- The environmental impacts of bio-based materials span a large range. This finding is partially attributable to the diversity of plausible methodological choices and assumptions and asks for caution when interpreting the outcome of this meta-analysis.
- Our analysis only quantifies part of the environmental impacts of bio-based materials. More comprehensive quantitative analyses should address, in particular, land use-related impacts (such as effects on biodiversity and soil organic matter, soil erosion) as well as the risks related to eco-toxicity and the use of genetically modified crops and microorganisms.
- Biomass cultivation with conventional farming practices, characterized by the application of mineral fertilizers, is the key contributor to the high eutrophication and stratospheric ozone depletion potentials of bio-based materials. These impacts can be reduced by improving fertilizer management and employing extensive farming practices. It should, however, be

considered that agricultural extensification, e.g., by decreasing the application of agrochemicals may result in lower crop yields, thus increasing land requirements for biomass production.

- The GHG emission savings identified here are subject to uncertainties because the reviewed LCA studies (i) may only insufficiently account for N₂O emissions from biomass cultivation and (ii) exclude the effects of indirect land use change. Depending on product scenarios and time horizons, especially the latter factor may lower substantially the established GHG emission savings. Further research is warranted.

The entire life cycle of bio-based materials offers potentials for decreasing environmental impacts. Most critical might be the reduction of land use and its impacts on GHG emissions, eutrophication, and stratospheric ozone depletion. Three strategies could be pursued: (i) expanding the feedstock base by utilizing organic waste as well as forest and agricultural residues, (ii) deploying integrated biorefineries that allow a more complete use of the biomass, including lignocellulosic non-food crops and residues for producing bio-based materials, energy, fuels, and heat, and (iii) carbon cascading by using biomass first for material purposes and at the end of their life cycle for energy. In developing countries, increasing yields and optimizing agricultural production are of paramount importance. Existing potentials could be realized by applying innovative investment solutions (Herrero et al. 2010) that may also generate positive spill-over effects on food production. Together these measures may contribute to mitigate both land use pressure on natural habitats and competition for land between food, feed, as well as biomass for other purposes. A comprehensive accounting of global land use for both food and non-food biomass consumption would allow assessing the overall effect on direct and indirect land use change as a basis for policy adjustments (Bringezu et al. 2012).

To date, bio-based materials are produced largely by small-scale pilot plants. Progress in biotechnology, technological learning, up-scaling of production facilities,

and process integration will likely reduce both the environmental impacts and the costs of bio-based materials (Vink et al. 2010, Hermann et al., 2010a). To quantify existing possibilities, LCA results can be combined with assessments of the technical and economic potential of bio-based materials (e.g., Saygin et al. 2010). The extent to which bio-based materials can reduce industrial non-renewable energy use and GHG emissions will crucially depend on their market diffusion. In spite of current growth rates, bio-based materials will require at least a decade to reach substantial market shares, even at high fossil fuel prices (Shen et al. 2009b; Saygin and Patel 2010). In any case, the impact of bio-based materials on the economy-wide non-renewable energy use and GHG emissions will remain limited because non-energy use for synthetic materials production accounts for only 6% of the global fossil fuel supply. The vast majority of fossil fuels is thus consumed for energy elsewhere in the economy (IEA 2009).

This meta-analysis has highlighted the environmental potentials and challenges of bio-materials. Addressing these challenges may indeed enable bio-based materials to substantially decrease the environmental impacts resulting from the production, use, and disposal of industrially manufactured materials.

Acknowledgements

The views expressed in this article are purely those of the authors and may not, under any circumstances, be regarded as an official position of the European Commission. We thank Garvin A. Heath (National Renewable Energy Laboratory, USA), Alexandra M. Newman (Colorado School of Mines, USA), Juliana Stropp (European Commission – Joint Research Centre, Italy), and three anonymous reviewers for their valuable comments on earlier drafts of this article.

6 References

- Akiyama, M., T. Tsuge, and Y. Doi. 2003. Environmental life cycle comparison of polyhydroxyalkanoates produced from renewable carbon resources by bacterial fermentation. *Polymer Degradation and Stability* 80(1): 183-194.
- Albrecht, S., S. Rüter, J. Welling, M. Knauf, U. Mantau, A. Braune, M. Baitz, H. Weimar, S. Sörgel, and J. Kreissig. 2008. *ÖkoPot - Ökologische Potenziale durch Holznutzung gezielt fördern*. [Targeted support for utilizing the environmental potentials of wood.] Final report BMBF-Project, FKZ 0330545. Stuttgart: Johann-Heinrich von Thünen Institut.
- Althaus, H.-J., F. Dinkel, C. Stettler, and F. Werner. 2007. *Life-cycle inventories of renewable materials*. Final report ecoinvent data v2.0 No. 21. Dübendorf: EMPA, Swiss Centre for Life-Cycle Inventories.
- Amlinger, F., S. Peyr, and C. Cuhls. 2008. Greenhouse gas emissions from composting and mechanical biological treatment. *Waste Management & Research* 26(1): 47–60.
- Ardente, F., M. Beccali, M. Cellura, and M., Mistretta. 2008. Building energy performance: A LCA case study of kenaf-fibres insulation board. *Energy and Buildings* 40(1): 1-10.
- Arima, E. Y., P. Richards, R. Walker, and M. M. Caldas. 2011. Statistical confirmation of indirect land use change in the Brazilian Amazon. *Environmental Research Letters* 6: 1-7.
- Bartmann, D., H. Peters, U. Lübker, A. Lott, W. Sack, J. O. Metzger, A. Diehlmann, and G. Kreisel. 2000. *Strahlenpolymerisierbare lösemittelfreie Schutz- und Dekorationsbeschichtungen für Holz und Holzwerkstoffe auf Basis nachwachsender heimischer Rohstoffe*. [Bio-based solvent-free lacquers and paints for wood and wood-based materials] Oldendorf-Holzhausen: DREISOL GmbH & Co KG.
- Boustead, I. 2005a. *Eco-profiles of the European Plastics Industry - High Density Polyethylene (HDPE)*. PlasticsEurope. Brussels, Belgium.
- Boustead, I. 2005b. *Eco-profiles of the European Plastics Industry - Low Density Polyethylene (LDPE)*. PlasticsEurope. Brussels, Belgium.

- Boustead, I. 2005c. *Eco-profiles of the European Plastics Industry - Polyethylene Terephthalate (PET, amorphous grade)*. PlasticsEurope. Brussels, Belgium.
- Boustead, I. 2005d. *Eco-profiles of the European Plastics Industry - Polypropylene (PP)*. PlasticsEurope. Brussels, Belgium.
- Brandão M. and A. Levasseur. 2011. *Assessing temporary carbon storage in life cycle assessment and carbon footprinting: Outcomes of an expert workshop*. Publications Office of the European Union. ISBN 978-92-79-20350-3. Luxembourg. Europe.
- Bringezu, S., M. O'Brien, H. Schütz. 2012. Beyond biofuels: Assessing global land use for domestic consumption of biomass. A conceptual and empirical contribution to sustainable management of global resources. *Land Use Policy* 29: 24-232.
- Bringezu, S. and R. Bleischwitz. (eds.) 2009. *Sustainable resource management: Global trends, visions and policies*. Sheffield: Greenleaf Publishing Limited.
- Bringezu, S., H. Schütz, M. O'Brien, L. Kauppi, R.W. Howarth, and J. McNeely. 2009. *Towards sustainable production and consumption of resources: Assessing biofuels*. Geneva, Nairobi: UNEP – United Nations Environment Programme..
- Bruinsma, J. 2009. The resource outlook to 2050: By how much do land, water, and crop yields need to increase by 2050? Paper presented at the FAO Expert Meeting, 24-26 June, Rome.
- Cherubini, F., N. D. Bird, A. Cowie, G. Jungmeier, B. Schlamadinger, S. Woess-Gallasch. 2009. Energy- and greenhouse gas-based LCA of biofuel and bioenergy systems: Key issues, ranges and recommendations. *Resources, Conservation and Recycling* 53: 434–447.
- Cherubini, F. and G. Jungmeier. 2010. LCA of a biorefinery concept producing bioethanol, bioenergy, and chemicals from switchgrass. *International Journal of Life Cycle Assessment* 15(1): 53-66.
- Corbière-Nicollier, T., B. Gfeller-Laban, L., Lundquist, J.-A. E. Leterrier, Y., Månson, and O. Jolliet. 2001. Life cycle assessment of bio fibres replacing glass fibres as reinforcement in plastics. *Resources, Conservation and Recycling* 33(4): 267-287.

- Crutzen, P.J., A. R. Mosier, K. A. Smith, and W. Winiwarter. 2007. N₂O release from agro-biofuel production negates global warming reduction by replacing fossil fuels. *Atmospheric Chemistry and Physics Discussions* 7: 11191–11205.
- Deimling, S., M. Goymann, M. Baitz, and T. Rehl. 2007. *Auswertung von Studien zur ökologischen Betrachtung von nachwachsenden Rohstoffen bei einer stofflichen Nutzung*. [Analyzing studies on the ecological evaluation of biomass use for materials] FKZ 114-50.10.0236/06-E. Leinfelden- Echterdingen: PE International.
- Diener, J. and U. Siehler. 1999. Ökologischer Vergleich von NMT- und GMT-Bauteilen. *Angewandte Makromolekulare Chemie* 272(1): 1-4.
- Dinkel, F., C. Pohl, M. Ros, and B. Waldeck. 1996. *Ökobilanz stärkehaltiger Kunststoffe*. [Life Cycle Assessment of starch-based polymers] Schriftenreihe Umwelt Nr. 271/I-II. Bern: Bundesamt für Umwelt, Wald und Landschaft (BUWAL).
- Dinkel, F. and B. Waldeck. 1999. *Ökologische Beurteilung verschiedener Geschirrtypen mit Empfehlungen*. [Ecological evaluation of various types of dishes] Arbeitspapier 4/99. Basel: Carbotech AG.
- Dornburg, V., I. Lewandowski, and M. K. Patel. 2004. Comparing the land requirements, energy savings, and greenhouse gas emissions reduction of bio-based polymers and bioenergy. *Journal of Industrial Ecology*. Volume 7(3-4): 93-116.
- Dreyer, L. C., A. L. Niemann, M. Z. Hauschild 2003. Comparison of three different LCIA methods: EDIP97, CML2001 and Eco-indicator 99. Does it matter which one you choose. *International Journal of Life Cycle Assessment* 8(4): 191–200.
- EA. 2001. *A national approach to waste tyres*. EA – Environment Australia. Canberra: Atech Group. www.environment.gov.au/settlements/publications/waste/tyres/nationalapproach/pubs//national-approach.pdf. Accessed: 2 May 2010.
- Edelmann, W. and K. Schleiss. 2001. *Ökologischer, energetischer und ökonomischer Vergleich von Vergärung, Kompostierung und Verbrennung fester biogener Abfallstoffe*. [Ecological, energetic, and economic comparison of fermentation,

- composting, and incineration of solid biogenic waste] Bern: Bundesamt für Energie (BFE) and Bundesamt für Umwelt, Wald und Landschaft (BUWAL).
- Egger. 2008. *Umweltproduktdeklaration von Laminatböden nach ISO 14025: Egger Laminatboden*. [Product declaration of floor laminate according to ISO 14025] Wismar: Egger Floor Products GmbH. http://www.egger.com/pdf/ZF_EPD_Laminatfussboden_DE.pdf. Accessed 2 May 2010.
- EIA. 2011. *International energy outlook 2011*. EIA – U.S. Energy Information Administration. Report DOE/EIA-0484. Washington, USA.
- Estermann, R., B. Schwarzwälder, and B. Gysin. 2000. *Life cycle assessment of Mater-Bi and EPS loose fills*. Novara: Study prepared by COMPOSTO for Novamont.
- Finnveden, G., M. Z. Hauschild, and T. Ekvall, J. Guinée, R. Heijungs, S. Hellweg, A. Koehler, D. Pennington, and S. Suh. 2009. Recent developments in life cycle assessment. *Journal of Environmental Management* 91(1): 1-21.
- Flake, M., T. Fleissner, and A. Hansen. 2000. *Ökologische Bewertung des Einsatzes nachwachsender Rohstoffe für Verkleidungskomponenten im Automobilbau*. [Ecological evaluation of using renewable resources in the automotive industry] Braunschweig: University Braunschweig.
- Gärtner S. O., K. Müller-Sämann, G. A. Reinhardt, and R. Vetter. 2002. Corn to plastics: a comprehensive environmental assessment. In *Proceedings of the 12th European Conference on Biomass for Energy, Industry and Climate Protection*, edited by W. Pala. et al., vol. II, pp.1324-1326. Amsterdam.
- Geyer, R., J. P. Lindner, D. M. Stoms, F. W. Davis, and B. Wittstock. 2010a. Coupling GIS and LCA for biodiversity assessments of land use; Part 1: Inventory modeling. *The International Journal of Life Cycle Assessment* 15(5): 454–467.
- Geyer, R., J. P. Lindner, D. M. Stoms, F. W. Davis, and B. Wittstock. 2010b. Coupling GIS and LCA for biodiversity assessments of land use; Part 2: Impact assessment. *The International Journal of Life Cycle Assessment* 15(7): 692-703.
- Gironi, F. and V. Piemonte. 2011. Bioplastics and petroleum-based plastics: Strengths and weaknesses. *Energy Sources, Part A* 33: 1949-1959.

- Groot, W. J. and T. Borén. 2010. Life cycle assessment of the manufacture of lactide and PLA biopolymers from sugar cane in Thailand. *International Journal of Life Cycle Assessment* 15(9): 970-984.
- Guinée, J. B. (final ed.) 2001. LCA - An operational guide to the ISO standards, Part 1, 2, 3. Institute of Environmental Science (CML), Leiden University. Leiden, The Netherlands.
- Guinée, J. B., R. Heijungs, and E. van der Voet. 2009. A greenhouse gas indicator for bioenergy: some theoretical issues with practical implications. *The International Journal of Life Cycle Assessment* 14(4): 328-339.
- Guo, M., A. P. Trzcinski, D. C. Stuckey, and R. J. Murphy. 2011. Anaerobic digestion of starch-polyvinyl alcohol biopolymer packaging: Biodegradability and environmental impact assessment. *Bioresource Technology* 102: 11137-11146.
- Harding, K. G., J. S. Dennis, H. von Blottnitz, and S. T. L. Harrison. 2007. Environmental analysis of plastic production processes: Comparing petroleum-based polypropylene and polyethylene with biologically-based poly- β -hydroxybutyric acid using life cycle analysis. *Journal of Biotechnology* 130(1): 57-66.
- Haufe, J. 2010. Energie- und Treibhausgas-Einsparungen durch die Nutzung nachwachsender Rohstoffe (Langfassung). In: Carus, M., A. Raschka, and S. Piotrowski. 2010. *Entwicklung von Förderinstrumenten für die stoffliche Nutzung von Nachwachsenden Rohstoffen in Deutschland - Volumen, Struktur, Substitutionspotenziale, Konkurrenzsituation und Besonderheiten der stofflichen Nutzung sowie Entwicklung von Förderinstrumenten*. [The development of instruments to support the material use of renewable raw materials in Germany.] Report-FKZ: 22003908. Hürth: nova-Institut.
- Havinga, J. 2003. How green is natural rubber? In *Natuurrubber* (Natural Rubber - Newsletter of the Rubber Foundation 30, 2nd quarter 2003. Eindhoven: Information Center for Natural Rubber. www.rubber-stichting.info/. Accessed 2 May 2010.
- Heijungs, R., J. B. Guinée, G. Huppes R. M. Lankreijer, H. A. Udo de Haes, A. Wegener Sleeswijk, A. M. M. Ansems, P. G. Eggels, R. van Duin, H. P. Goede. 1992.

- Environmental life cycle assessment of products - background and guide*. NL-2300 RA. Centre of Environmental Science (CML), Leiden, The Netherlands.
- Hermann, B. G., K. Blok, and M. K. Patel. 2010a. Twisting bio-based materials around your little finger: environmental impacts of bio-based wrappings. *The International Journal of Life Cycle Assessment* 15(4) 346-458.
- Hermann, B. G., L. Debeer, B. de Wilde, K. Blok, and M. K. Patel. 2010b. To compost or not to compost: LCA of biodegradable materials' waste treatment. Submitted for publication.
- Herrero, M., P. K. Thornton, A. M. Notenbaert, S. Wood, S. Msangi, H. A. Freeman, D. Bossio, J. Dixon, M. Peters, J. van de Steeg, J., Lynam, P. Parthasarathy Rao, S. Macmillan, B. Gerard, J. McDermott, C. Seré, and M. Rosegrant. 2010. Smart investments in sustainable food production: revisiting mixed crop-livestock systems. *Science* 327(5967): 822 – 825.
- Hoefnagels, R., E. M. W. Smeets, and A. Faaij. 2010. Greenhouse gas footprints of different production systems. *Renewable and Sustainable Energy Reviews* 14(7): 1661-1694.
- Hubert, B., M. Rosegrant, M. A. J. S. van Boekel, and R. Ortiz. 2010. The future of food: Scenarios for 2050. *Crop Science* 50(2): 33-50.
- IAI. 2010. *Historic IAI statistics*. London: IAI – International Aluminium Institute. https://stats.world-aluminium.org/iai/stats_new/index.asp. Accessed 3 August 2010.
- IEA. 2009. *Energy balances of non-OECD countries*. Paris: IEA, Organization for Economic Cooperation and Development.
- IEA. 2010. *Key world energy statistics*. Paris: IEA, Organization for Economic Cooperation and Development.
- IPCC. 2006. *2006 IPCC Guidelines for national greenhouse gas inventories*. Volume 4, Chapter 11. Geneva. www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_11_Ch11_N2O&CO2.pdf. Accessed 4 November 2010.
- ISO. 2006a. *Environmental management - Life cycle assessment - Principles and framework*. ISO 14040. Geneva: International Organization for Standardization.

- ISO. 2006b. *Environmental management - Life cycle assessment - Requirements and guidelines*. ISO/FDIS 14044. Geneva: International Organization for Standardization.
- Kaenzig, J., G. Houillon, M. Rocher, H. Bewa, L. Bodineau, M. Orphelin, E. Poitrat, and O. Jolliet. 2004. Comparison of the environmental impacts of bio-based products. *Proceedings of the 2nd World Conference and Technology Exhibition on Biomass for Energy, Industry and Climate Protection*. 10-14 May. Rome.
- Karpenstein-Machan, M. 2001. Sustainable cultivation concepts for domestic energy production from biomass. *Critical Reviews in Plant Sciences* 20(1): 1-14.
- Kim, S., and B. E. Dale. 2005. Life cycle assessment study of biopolymers (polyhydroxy-alkanoates) derived from no-tilled corn. *The International Journal of Life Cycle Assessment* 10(3): 200-210.
- Kim, S., and B. E. Dale. 2008. Energy and greenhouse gas profiles of polyhydroxybutyrates derived from corn grain: A life cycle perspective. *Environmental Science & Technology* 42(20): 7690-7695.
- Khoo, H. H., R. B. H. Tan, and K. W. L. Chng. 2010. Environmental impacts of conventional plastic and bio-based carrier bags - Part 1: Life cycle production. *International Journal of Life Cycle Assessment* 15(3): 284-293.
- KTBL. 2008. *Ökologische und ökonomische Bewertung nachwachsender Energieträger*. [Ecological evaluation of renewable energy resources.] KTBL-Vortragstagung, 8-9 September 2008 in Aschaffenburg. Darmstadt: KTBL - Kuratorium für Technik und Bauwesen in der Landwirtschaft e.V.
- Lapola, D. M., R. Schaldach, J. Alcamo, A. Bondeau, J. Kocha, K. Koelking, and J. A. Priess. 2010. Indirect land use changes can overcome carbon savings from biofuels in Brazil. *PNAS* 107(49): 3388-3393.
- Larson, E. D. 2006. A review of life-cycle analysis studies on liquid biofuel systems for the transport sector. *Energy for Sustainable Development* 10(2): 109-126.
- Lasserre, P. 2008. *Global strategic management - The global cement industry*. http://philippelasserre.net/contenu/Download/Global_Cement_industry.pdf. Accessed 3 August 2010.

- Le Duigou, A., J.-M. Deux, P. Davies, and C. Baley. 2011. PLLA/flax mat/balsa bio-sandwich - environmental impact and simplified life cycle analysis. *Applied Composite Materials*, DOI 10.1007/s10443-011-9201-3.
- Macedo, I. C., J. E. A. Seabra, and J. E. A. R. Silva. 2008. Green house gas emissions in the production and use of ethanol from sugarcane in Brazil: The 2005/2006 averages and a prediction for 2020. *Biomass and Bioenergy* 32(7): 582-595.
- Madival, S., R. Auras, S. P. Singh, and R. Narayan. 2009. Assessment of the environmental profile of PLA, PET and PS clamshell containers using LCA methodology. *Journal of Cleaner Production* 17: 1183-1194.
- McManus, M.C., G. P. Hammond, and C. R. Burrows. 2004. Life-cycle assessment of mineral and rapeseed oil in mobile hydraulic systems. *Journal of Industrial Ecology* 7(3-4): 163-177.
- Miller, S.A., A. E. Landis, T. L. Theis, and R. A. Reich. 2007. A comparative life cycle assessment of petroleum and soybean-based lubricants. *Environmental Science and Technology* 41(11): 4143-4149.
- Müller-Sämann, K. M., G. A. Reinhardt, R. Vetter, and S. O. Gärtner. 2002. Nachwachsende Rohstoffe in Baden-Württemberg: *Identifizierung vorteilhafter Produktlinien zur stofflichen Nutzung unter Berücksichtigung umweltgerechter Anbauverfahren*. [Biomass resources in Baden-Württemberg: Identifying environmentally favorable bio-based products.] Report FZKA-BWPLUS, BWA 20002. Mühlheim: Institut für umweltgerechte Landbewirtschaftung (IfuL) and Heidelberg: Institut für Energie- und Umweltforschung Heidelberg GmbH (IFEU).
- Nebel, B., Zimmer, B., and Wegener, G. (2006): Life cycle assessment of wood floor coverings: A representative study for the German flooring industry. *The International Journal of Life Cycle Assessment* 11(3): 172-182.
- Nellemann, C., M. MacDevette, T. Manders, B. Eickhout, B. Svihus, A. Gerdien-Prins, and B. P. Kaltenborn. 2009. *The environmental food crisis: The environment's role in averting future food crises - A UNEP rapid response assessment*. Nairobi: United Nations Environment Programme.
- Ness, B., E. Urbel-Piirsalu, S. Anderberg, and L. Olsson. 2007. Categorising tools for sustainability assessment. *Ecological Economics* 60(3): 498-508.

- OGJ. 2007. 2007 Worldwide refinery survey. *Oil and Gas Journal*. Tulsa: PennWell Corporation.
- Ogle, S. M., S. J. Del Grosso, P. R. Adler and W. J. Parton (2008): Soil nitrous oxide emissions with crop production for biofuel: Implications for greenhouse gas mitigation. Farm Foundation; Oak Brook, USA: http://www.farmfoundation.info/news/articlefiles/371-the_lifecycle_carbon_footprint_of_biofuels.pdf#page=20. Accessed: 15 September 2011.
- Oertel, D. 2007. *Industrielle stoffliche Nutzung nachwachsender Rohstoffe. Sachstandsbericht zum Monitoring Nachwachsende Rohstoffe*. [The industrial use of biomass. Report on the monitoring of biogenic resources.] Arbeitsbericht 114. Berlin: www.tab.fzk.de/de/projekt/zusammenfassung/ab114.pdf. Accessed 13 April 2010.
- Patel, M.K., M. Crank, V. Dornburg, B. G. Hermann, L. Roes, B. Hüsing, L. Overbeek, F. Teragagni, and E. Recchia. 2006. *Medium- and long-term opportunities and risks of the biotechnological production of bulk chemicals from renewable resources – The potential of white biotechnology*. The BREW Project – Final Report. Utrecht: Utrecht University.
- Patel, M. K., C. Bastioli, L. Marini, and E. Würdinger. 2003. Life-cycle assessment of bio-based polymers and natural fiber composites. In *Encyclopedia "Biopolymers,"* Vol. 10, Weinheim: Wiley-VCH.
- Patel, M. K., G. A. Reinhardt, and G. Zemanek (1999): Vegetable oils for biofuels versus surfactants: An ecological comparison for energy and greenhouse gases. *Fett/Lipid* 101(9): 314-320.
- Pervaiz, M., and M. M. Sain. 2003. Carbon storage potential in natural fiber composites. *Resources, Conservation and Recycling* 39(4): 325-340.
- PlasticsEurope. 2007. *Business data and charts 2006*. Brussels: PlasticsEurope Market Research Group (PEMRG).
- Plevin, R. J., M. O'Hare, A. D. Jones, M. S. Torn, and H. K. Gibbs. 2010. Greenhouse gas emissions from biofuels' indirect land use change are uncertain but may be much

- greater than previously estimated. *Environmental Science and Technology* 44(21): 8015-8021.
- Piemonte, V., F. Gironi. 2010. Land use change emissions: How green are the bioplastics? Wiley Online Library. DOI 10.1002/ep.10518:1-7.
- Pless, P. S. 2001. *Technical and environmental assessment of thermal insulation materials from bast fiber crops*. Los Angeles: University of California.
- Quirin, M., S. O. Gärtner, M. Pehnt, and G. A. Reinhardt. 2004. *CO₂-neutrale Wege zukünftiger Mobilität durch Biokraftstoffe: Eine Bestandsaufnahme*. [CO₂-neutral pathways towards future mobility: The current situation of biofuels.] Heidelberg: Institut für Energie- und Umweltforschung Heidelberg GmbH (IFEU). [www.ufop.de/downloads/Co2_neutrale_ Wege.pdf](http://www.ufop.de/downloads/Co2_neutrale_Wege.pdf). Accessed 2 May 2010.
- Ravishankara, A.R., J. S. Daniel, and R. W. Portmann. 2009. Nitrous oxide (N₂O): The dominant ozone-depleting substance emitted in the 21st Century. *Science* 326(5949): 123-125.
- Reis Neto, O. P. 2007. *Bio-based polyolefin initiative*. São Paulo: Braskem S.A.
- Reinhardt, G. A., A. Detzel, S. O. Gärtner, N. Rettenmaier, and M. Krüger. 2007. *Nachwachsende Rohstoffe für die chemische Industrie: Optionen und Potenziale für die Zukunft*. [Biomass for the chemical industry: Future options and potentials] Heidelberg: Institut für Energie- und Umweltforschung Heidelberg GmbH (IFEU).
- Reinhardt, G. A. and S. O. Gärtner. 2003. Biodiesel or pure Rape-seed Oil for Transportation: Which one is best for the environment? In *Proceedings of the 4th International Colloquium "Fuels 2003,"* Ostfildern, 15-16 January 2003, pp. 111-114. Esslingen: Technische Akademie Esslingen.
- Reinhardt, G. A., R. Herbener, and S. O. Gärtner. 2001. *Life-cycle analysis of lubricants from rape seed oil in comparison to conventional lubricants*. Heidelberg: Institut für Energie- und Umweltforschung Heidelberg (IFEU). www.brdisolutions.com/pdfs/bcota/abstracts/13/z312.pdf. Accessed 2 May 2010.

- Reinhardt, G. A. and Zemanek, G. 2000. *Ökobilanz Bioenergieträger: Basisdaten, Ergebnisse, Bewertungen*. [Life Cycle Assessment of bioenergy: Data, results, and evaluations] Berlin: Erich Schmidt Verlag.
- Reinhardt, G. A., A. Patyk, J. Calzoni, N. Caspersen, N. Dercas, G. Gaillard, G. Gosse, M. Hanegraaf, L. Heinzer, N. Jungk, A. Kool, G. Korsuize, M. Lechner, B. Leviel, R. Neumayr, A. M. Nielsen, P. H. Nielsen, A. Nikolaou, C. Panoutsou, A. Panvini, J. Rathbauer, G. Riva, E. Smedile, C. Stettler, B. Pedersen Weidema, M. Wörgetter, and H. van Zeijts. 2000. *Bioenergy for Europe: Which one fits best? – A comparative analysis for the community*. Final Report FAIR V CT 98 3832. Heidelberg: IFEU – Institut für Energie- und Umweltforschung Heidelberg GmbH.
- Ren, T. and M. K. Patel. 2009. Basic petrochemicals from natural gas, coal and biomass. Energy use and CO₂ emissions. *Resources, Conservation and Recycling* 53(9): 513-528.
- Rettenmaier, N., G. A. Reinhardt, S. Gärtner, and J. Münch. 2008. *Bioenergie aus Getreide und Zuckerrübe: Energie- und Treibhausgasbilanzen*. [Bioenergy from grain and sugar beet: Energy and greenhouse gas balances] Heidelberg: Institut für Energie- und Umweltforschung Heidelberg GmbH (IFEU). www.ifeu.org/landwirtschaft/pdf/IFEU%20-%20Bioenergie%20LAB%20%20Kurzversion.pdf. Accessed 2 May 2010.
- Rothermel, J. 2008. *Raw material change in the chemical industry – The general picture*. HLG Chemicals – Working Group Feedstock, Energy & Logistics. Presentation given in Brussels, Belgium for the German Chemical Industry Association (VCI).
- Saygin, D. and M. K. Patel. 2010. *Renewables for industry: An overview of the opportunities for biomass use*. Prepared for the United Nations Industrial Development Organization (UNIDO), Energy and Climate Change Branch. Utrecht: Utrecht University.
- Schmitz, N., J. Henke, and G. Klepper. 2009. *Biokraftstoffe - Eine vergleichende Analyse*. [Biofuels – A comparative analysis] Gülzow: Fachagentur Nachwachsende Rohstoffe. Biokraftstoffe - Eine vergleichende Analyse. Accessed 2 May 2011.

- Searchinger, T., R. Heimlich, R.A., Houghton, F. Dong, A. Elobeid, J. Fabiosa, S. Tokgoz, D. Hayes, and T.-H. Yu. 2010. Use of U.S. cropland for biofuels increases greenhouse gases through emissions from land use change. *Science* 319(5867): 1238-1240.
- Sharai-Rad, M., and J. Welling. 2002. *Environmental and energy balances of wood products and substitutes*. Rome: FAO, Food and Agriculture Organization of the United Nations.
- Shen, L., and M. K. Patel. 2010. Life cycle assessment of man-made cellulose fibres. *Lenzinger Berichte* 88: 1-59.
- Shen, L., J. Haufe, and M. K. Patel. 2009a. *Product overview and market projection of emerging bio-based plastics*. PRO-BIP 2009. Utrecht: Utrecht University.
- Shen, L, E. Worrell, and M. K. Patel. 2009b. Present and future development in plastics from biomass. *Biofuels, Bioproducts & Biorefining* 4(1): 25-40.
- Shen, L. and M. K. Patel. 2008. Life cycle assessment of polysaccharide materials: A review. *Journal of Polymers and the Environment* 16(2): 154-167.
- Sleeswijk, A. W., L. F. C. M. van Oers, J. B. Guinée, J. Struijs, and M. A. J. Huijbregts. 2008. Normalisation in product life cycle assessment: An LCA of the global and European economic systems in the year 2000. *Science of the Total Environment* 390: 227-240.
- Smeets, E. M. W., L. F. Bouwman, E. Stehfest, D. P. van Vuuren, D.P., and A. Postuma. 2009. Contribution of N₂O to the greenhouse gas balance of first-generation biofuels. *Global Change Biology* 15: 1-23.
- Tufvesson, L. and P. Börjesson. 2008. Wax production from renewable feedstock using biocatalysts instead of fossil-based feedstock and conventional methods. *The International Journal of Life Cycle Assessment* 13(4): 328-338.
- Turunen, L. and H. M. G. van der Werf. 2006. *Life cycle assessment of hemp textile yarn - comparison of three hemp fiber processing scenarios and a flax scenario*. Paris: Institut National de la Recherche Agronomique (INRA).
- UBA 1995. *Methodik der produktbezogenen Ökobilanzen – Wirkungsbilanz und Bewertung (Methods for life cycle assessment – impact assessment)* UBA – Federal Environmental Agency. UBA-Texte 23/95. Berlin, Germany.

- UN. 2008. *Industry commodity production data 1950–2005*. CD-ROM. New York: UN, United Nations Statistics Division.
- UNEP. 2000. *The Montreal Protocol on substances that deplete the ozone layer*. Nairobi: UNEP, United Nations Environmental Programme.
- Vidal, R., P. Martínez, and D. Garraín. 2009. Life cycle assessment of composite materials made of recycled thermoplastics combined with rice husks and cotton linters. *The International Journal of Life Cycle Assessment* 14(1): 73-82.
- Vidal, R., P. Martínez, E. Mulet, R. González, B. López-Mesa, P. Fowler, and J. M. Fang. 2007. Environmental assessment of biodegradable multilayer film derived from carbohydrate polymers. *Journal of Polymers and the Environment* 15(3): 159–168.
- Vink, E. T. H., S. Davies, and J. J. Kolstad. 2010. The eco-profile for current Ingeo® polylactide production. *Industrial Biotechnology* 6(4): 212-224.
- Vink, E. T. H., D. A. Glassner, J.J. Kolstad, R.J. Wooley, and R.P. O'Connor. 2007. The eco-profiles for current and near-future NatureWorks® polylactide (PLA) production. *Industrial Biotechnology* 3(1): 58-81.
- von Blottnitz, H., and M. A. Curran. 2007. A review of assessments conducted on bio-ethanol as a transportation fuel from a net energy, greenhouse gas, and environmental life cycle perspective. *Journal of Cleaner Production* 15(7): 607-619.
- WBGU. 2008. *Welt im Wandel: Zukunftsfähige Bioenergie und nachhaltige Landnutzung*. [A changing world: Sustainable bioenergy and land use.] Berlin: Wissenschaftlicher Beirat der Bundesregierung für Globale Umweltveränderungen (WBGU).
- Weiss, M. and M. K. Patel. 2007. On the environmental performance of bio-based energy, fuels, and materials: a comparative analysis of life cycle assessment studies, In *Renewable resources and renewable energy: a global challenge*, edited by M. Graziani, M. and P. Fornasiero. Taylor & Francis CRC Press.
- Weiss, M., M. K. Patel, H. Heilmeier, and S. Bringezu. 2007. Applying distance-to-target weighing methodology to evaluate the environmental performance of bio-based energy, fuels, and materials. *Resources, Conservation and Recycling* 50(3): 260-281.

- Weiss, M. 2003. Flächenbezogener Vergleich von Umweltbelastungen durch Produkte auf Basis nachwachsender und fossiler Grundstoffe. [Land use-based comparison of the environmental impacts of products manufactured from renewable and fossil resources.] Master Thesis. TU Bergakademie Freiberg. Freiberg, Germany.
- Williams, P. R. D., D. Inman, A. Aden, G.A. Heath. 2009. Environmental and sustainability factors associated with next-generation biofuels in the U.S.: What do we really know? *Environmental Science and Technology* 43(13): 4763-4775.
- Wicke, B., V. Dornburg, H. M. Junginger, and A. Faaij. 2008. Different palm oil production systems for energy purposes and their greenhouse gas implications. *Biomass and Bioenergy* 32(12): 1322-1337.
- Wightman, P., R. Eavis, S. Batchelor, K. Walker, R. Bennett, P. Carruthers, and R. Tranter. 1999. Comparison of rapeseed and mineral oils using life-cycle assessment and cost-benefit analysis. *OCL – Oléagineux, corps gras, lipides* 6(5): 384-388.
- Wötzel, K., R. Wirth, and M. Flake. 1999. Life cycle studies on hemp fiber reinforced components and ABS for automotive sections. *Die Angewandte Molekulare Chemie* 272(1): 121-127.
- Würdinger, E., U. Roth, A. Wegener, R. Peche, W. Rommel, S. Kreibe, A. Nikolakis, I. Rüdénauer, C. Pürschel, P. Ballarin, T. Knebel, J. Borken, A. Detzel, H. Fehrenbach, J. Giegrich, S. Möhler, A. Patyk, G. A. Reinhardt, and R. Vogt. 2002. *Kunststoffe aus nachwachsenden Rohstoffen: Vergleichende Ökobilanz für Loose-fill-Packmittel aus Stärke bzw. Polystyrol*. [Polymers from starch: A comparative life cycle assessment for loose-fill packaging materials from starch and polystyrene.] Projektgemeinschaft BIfA / IFEU / Flo-Pak. DBU-Az. 04763. Heidelberg: Institut für Energie- und Umweltforschung Heidelberg GmbH (IFEU).
- Zah, R., R. Hirschler, A. L., Leão, and I. Braun. 2007. Curauá fibers in the automobile industry - a sustainability assessment. *Journal of Cleaner Production* 15(11-12): 1032-1040.

Appendix

Table A1: Overview of LCA studies and environmental impact categories; impacts are reported per metric ton of bio-based material [t^{-1}] and per hectare of agricultural land and year [$(ha*a)^{-1}$] used to produce bio-based feedstock; system boundaries refer to cradle-to-factory gate (C-FG) or cradle-to-grave (C-G)

Reference	Product group	System boundary	Number of product scenarios	NREU		Climate change		Eutrophication		Acidification		Stratospheric ozone depletion		Photochemical ozone formation	
				t^{-1}	$(ha*a)^{-1}$	t^{-1}	$(ha*a)^{-1}$	t^{-1}	$(ha*a)^{-1}$	t^{-1}	$(ha*a)^{-1}$	t^{-1}	$(ha*a)^{-1}$	t^{-1}	$(ha*a)^{-1}$
Shen and Patel (2010) ^g	Textiles	C-FG	5	x	x ^o	x	x ^o	x	-	x	-	-	-	x	-
Althaus et al. (2007) ^g	Textiles	C-FG	4	x	x ^o	x	x ^o	-	-	-	-	-	-	-	-
Vink et al. (2007) ^g	Textiles	C-FG	1	x	x ^o	x	x ^o	-	-	-	-	-	-	-	-
Patel et al. (2006) ^g	Textiles	C-FG	1	x	x ^o	x	x ^o	-	-	-	-	-	-	-	-
Turunen and van der Werf (2006) ^g	Textiles	C-FG	4	x	x ^o	x	x ^o	x	-	x	-	-	-	-	-
Groot and Borén (2010)	Plastics	C-FG	1	x ^a	-	x ^a	-	x ^a	-	x ^a	-	-	-	x ^a	-
Hermann et al. (2010b)	Plastics	C-FG	42	x ^q	-	x ^q	-	-	-	-	-	-	-	-	-
Khoo et al. (2010)	Plastics	C-FG	1	-	-	x	-	-	-	-	-	-	-	-	-
Vink et al. (2010)	Plastics	C-FG	1	x ^a	-	x ^a	-	-	-	-	-	-	-	-	-
Madival et al. (2009)	Plastics	C-G	2	x	-	x	-	x ^p	-	x ^p	-	-	-	x	-
Kim and Dale (2008)	Plastics	C-FG	1	x ^a	-	x ^a	-	-	-	-	-	-	-	-	-
Macedo et al. (2008); Reis Neto (2007) ⁱ	Plastics	C-FG	1	x ^a	x ^o	x ^a	x ^o	-	-	-	-	-	-	-	-
Vidal et al. (2007)	Plastics	C-FG	1	x	x ^o	x	x ^o	x	-	x	-	-	-	-	-
Vink et al. (2007) ^g	Plastics	C-FG	1	x	x ^o	x	x ^o	-	-	-	-	-	-	-	-
Harding et al. (2007) ⁱ	Plastics	C-FG	3 ^b	x	x ^o	x	x ^o	x	-	x	-	-	-	x	-
Patel et al. (2006)	Plastics	C-FG	3	x	x	x	x	-	-	-	-	-	-	-	-
Kim and Dale (2005) ⁱ	Plastics	C-FG	2	x	x ^o	x	x ^o	-	-	-	-	-	-	-	-
Akiyama et al. (2003) ⁱ	Plastics	C-FG	2	x	x ^o	x	x ^o	-	-	-	-	-	-	-	-
Müller-Sämann et al. (2002)	Plastics	C-G	2	-	x	-	x	-	x	-	x	-	x	-	-
Würdinger et al. (2002)	Plastics	C-G	4 ^b	x	x ^o	x	x ^o	x	x ^e	x	x ^e	x	x ^f	x	x ^f
Estermann et al. (2000) ^h	Plastics	C-G ^c	1	x	x ^o	x	x ^o	-	-	-	-	-	-	-	-
Dinkel et al. (1996)	Plastics	C-G ^{c,d}	4 ^b	x	x ^o	x	x ^o	-	x ^e	-	x ^e	-	x ^e	-	x ^e
Reinhardt et al. (2007)	Surfactants	C-FG	2	-	x	-	x	-	-	-	-	-	-	-	-

Patel et al. (1999)	Surfactants	C-G ^d	9	x	x ^o	x	x ^o	-	-	-	-	-	-	-	-
Müller-Sämann et al. (2002)	Insulation materials	C-G	2	-	x	-	x	-	x	-	x	-	x	-	-
Miller et al. (2007)	Hydraulic oils and lubricants	C-G	1	x	x	x	x	-	-	-	-	-	-	-	-
McManus et al. (2004)	Hydraulic oils and lubricants	C-FG	1	x	x	x	x	x	-	x	-	-	-	x	-
Müller-Sämann et al. (2002)	Hydraulic oils and lubricants	C-G	4	-	x	-	x	-	x	-	x	-	x	-	-
Reinhardt et al. (2001)	Hydraulic oils and lubricants	C-G	3	x	x	x	x	x	-	x	-	x	-	-	-
Patel et al. (1999)	Hydraulic oils and lubricants	C-FG	1	x	x ^k	x	x ^k	-	-	-	-	-	-	-	-
Wightman et al. (1999)	Hydraulic oils and lubricants	C-G	1	-	-	x	x	-	-	-	-	-	-	-	-
Havinga (2003); EA (2001) ^a	Rubber	C-FG	1	x	x ^o	x	x ^o	-	-	-	-	-	-	-	-
Le Duigou et al. (2011)	Composites	C-FG	2	x	-	x	-	-	-	-	-	-	-	-	-
Vidal et al. (2009)	Composites	C-FG	3 ^b	x	x ^o	x	x ^o	x	-	x	-	-	-	-	-
Zah et al. (2007)	Composites	C-FG	1	-	-	x	x ^l	x	-	x	-	-	-	x	-
Pervaiz and Sain (2003)	Composites	C-G	1	x	x ^o	x	x ^o	-	-	-	-	-	-	-	-
Müller-Sämann et al. (2002)	Composites	C-G	2	-	x	-	x	-	x	-	x	-	x	-	-
Corbière-Nicollier et al. (2001)	Composites	C-G	1	x	x ^o	x	x ^o	x	x ^e	x	x ^e	-	-	x	x ^f
Pless (2001)	Composites	C-FG	2	x	x ^o	x	x ^o	-	-	-	-	-	-	-	-
Flake et al. (2000)	Composites	C-FG	1	x	x ^o	-	-	-	-	-	-	-	-	-	-
Diener and Siehler (1999)	Composites	C-FG	1	x	x ^m	-	x ^f	x	x ^e	x	x ^e	-	-	-	-
Woetzel et al. (1999)	Composites	C-FG	1	x	x ^o	x	x ^o	x	x ^e	x	x ^e	x ^a	x ^f	x	x ^f
Tufvesson and Börjesson (2008)	Lacquer, paint, and waxes	C-FG	1	x	x	x	x	x	-	x	-	-	-	x	-
Bartmann et al. (2000)	Lacquer, paint, and waxes	C-FG	1	x	x ^a	x	x ^o	-	-	x	-	x	-	-	-
Albrecht et al. (2008); Egger (2008)	Floor boarding	C-G	2	x ^a	x ^o	x ^a	x ^o	-	-	-	-	-	-	-	-
Nebel et al. (2006); Egger (2008)	Floor boarding	C-G	12 ^m	x ^a	x ^o	x ^a	x ^o	x ^a	-	x ^a	-	-	-	x ^a	-
Sharai-Rad and Welling (2002)	Floor boarding	C-G	2 ⁿ	x ^a	x ^o	x ^a	x ^o	x ^a	-	x ^a	-	-	-	x ^a	-

- excluded from this review

^a own calculations based on information provided in the respective LCA study

^b only one product scenario considered in the impact categories NREU and climate change

^c C-FG for the impact category NREU

^d covering manufacturing and disposal only

^e as recalculated by Weiss and Patel (2007)

f as recalculated by Weiss (2003)

g data source for conventional materials: Boustead (2005c)

h data source for conventional materials: Boustead (2005b)

i data source for conventional materials: Boustead (2005a)

j data source for conventional materials: Boustead (2005d)

k own calculations based on a combination of information provided by Patel et al. (1999) and Reinhardt et al. (2001)

l own calculations based on miscellaneous data sources

m number of considered scenarios varies between impact categories

n only one scenario considered in the impact categories of NREU and climate change

o as recalculated by Haufe (2010)

p only considering aquatic eutrophication and acidification

q calculated based on data communicated by the authors of the LCA study for various wrapping materials

Table A2: Arithmetic mean and median of the environmental impacts of the nine groups of bio-based materials as compared to conventional product alternatives; uncertainty ranges represent the standard deviation of the data sample; the totals represents the arithmetic mean and the median of values identified for the nine groups of materials

	Non-renewable energy use in GJ				Climate Change in t CO ₂ -equivalents			
	t ⁻¹ (mean)	t ⁻¹ (median)	(ha*a) ⁻¹ (mean)	(ha*a) ⁻¹ (median)	t ⁻¹ (mean)	t ⁻¹ (median)	(ha*a) ⁻¹ (mean)	(ha*a) ⁻¹ (median)
Textiles	-50 ± 29	-60	-101 ± 86	-91	-2 ± 2	-2	-5 ± 4	-3
Plastics	-37 ± 25	-37	-184 ± 203	-108	-0.5 ± 6	-1	-8 ± 10	-6
Surfactants	-40 ± 10	-40	-296 ± 204	-141	-3 ± 1	-3	-19 ± 13	-12
Insulation materials	-	-	-71 ± 17	-71	-	-	-6 ± 1	-6
Hydraulic oils and lubricants	-40 ± 6	-39	-51 ± 14	-51	-2 ± 1	-2	-3 ± 1	-3
Rubber	-71	-71	-37	-37	-2	-2	-1	-1
Composites	-54 ± 42	-37	-137 ± 116	-102	-2 ± 2	-2	-7 ± 10	-4
Lacquer and paints	-130 ± 81	-130	-153 ± 150	-153	-6 ± 4	-6	-7 ± 5	-8
Floor boarding	-18 ± 21	-14	-115 ± 79	-92	-4 ± 1	-3	-12 ± 7	-10
<i>Total</i>	-55 ± 34	-39	-127 ± 79	-92	-3 ± 1	-2	-8 ± 5	-6

- not quantified

Table A2 (cont.):

	Eutrophication in kg PO ₄ -equivalents				Acidification in kg SO ₂ -equivalents			
	t ⁻¹ (mean)	t ⁻¹ (median)	(ha*a) ⁻¹ (mean)	(ha*a) ⁻¹ (median)	t ⁻¹ (mean)	t ⁻¹ (median)	(ha*a) ⁻¹ (mean)	(ha*a) ⁻¹ (median)
Textiles	17 ± 17	21	-	-	30 ± 31	24	-	-
Plastics	1 ± 2	0	22 ± 21	19	6 ± 15	4	-37 ± 53	-37
Surfactants	-	-	-	-	-	-	-	-
Insulation materials	-	-	1	1	-	-	2	2
Hydraulic oils and lubricants	2 ± 1	2	1 ± 2	1	7 ± 5	9	4 ± 0.1	4
Rubber	-	-	-	-	-	-	-	-
Composites	0 ± 2	-1	-2 ± 8	-3	-12 ± 7	-15	-127 ± 213	-25
Lacquer and paints	8	8	-	-	-25 ± 50	-25	-	-
Floor boarding	0 ± 2	0	-	-	-17 ± 45	3	-	-
<i>Total</i>	<i>5 ± 7</i>	<i>1</i>	<i>6 ± 11</i>	<i>10</i>	<i>-2 ± 20</i>	<i>4</i>	<i>-39 ± 61</i>	<i>-4</i>

- not quantified

Table A2 (cont.):

	Stratospheric ozone depletion in kg N ₂ O-equivalents				Photochemical ozone formation in kg ethane-equivalents			
	t ⁻¹ (mean)	t ⁻¹ (median)	(ha*a) ⁻¹ (mean)	(ha*a) ⁻¹ (median)	t ⁻¹ (mean)	t ⁻¹ (median)	(ha*a) ⁻¹ (mean)	(ha*a) ⁻¹ (median)
Textiles	-	-	-	-	-0.2 ± 0.6	-0.4	-	-
Plastics	0.4 ± 0.4	0.4	3.3 ± 1.8	3.3	-3.2 ± 5.9	-0.9	-49 ± 28	-41
Surfactants	-	-	-	-	-	-	-	-
Insulation materials	-	-	1.0	1.0	-	-	-	-
Hydraulic oils and lubricants	4.2 ± 0.01	4.2	4.1 ± 1.9	4.1	0.5	0.5	-	-
Rubber	-	-	-	-	-	-	-	-
Composites	0.6	0.6	1.7 ± 0.5	1.7	-1.9 ± 1.5	-2.5	-76 ± 95	-76
Lacquer and paints	2.4	2.4	1.9	1.9	-0.9	-0.9	-	-
Floor boarding	-	-	-	-	3.7 ± 21.9	9.4	-	-
<i>Total</i>	<i>1.9 ± 1.8</i>	<i>1.5</i>	<i>2.4 ± 1.3</i>	<i>1.9</i>	<i>-0.3 ± 2.4</i>	<i>-0.6</i>	<i>-62 ± 20</i>	<i>-58</i>

- not quantified

Table A3: Non-renewable primary energy use and GHG emissions of bio-based chemicals in comparison to conventional product alternatives
(Primary data source: Patel et al. 2006)

	Number of product scenarios (bio-based, fossil-based)	NREU in GJ/t	Climate change in t CO ₂ - equivalents/t
Ethanol	14,2	-55 ± 25	-3 ± 1
1,5 Pentandiol	27,3	-57 ± 41	-3 ± 2
Allyl butyl ether	18,1	-65 ± 30	-4 ± 2
Acetic acid	18,1	7 ± 37	0 ± 2
Acrylic acid	3,1	-30 ± 13	-2 ± 1
Succinic acid	18,2	-51 ± 37	-5 ± 2
Adipic acid	9,1	-19 ± 62	-2 ± 3
Caprolactam	3,1	-99 ± 25	-7 ± 1
Polyhydroxyalkanoates	36,1	-19 ± 41	0 ± 3
Ethylene	6,1	-66 ± 31	-4 ± 2
Ethyl lactate	15,5	-35 ± 28	-2 ± 2
Polylactic acid	21,3	-44 ± 19	-2 ± 2
Polytrimethylene terephthalate	27,5	-23 ± 17	-1 ± 1

Endnote

ⁱ The total global production of bulk materials reached approximately 6,500 Mt in 2009. This figure comprises the production of cement, iron and steel, bricks, glass, polymers and other petrochemicals, lubricants, bitumen, aluminum, textiles, wood, and paper (own estimates based on Deimling et al. 2007, Lasserre 2008, OGS 2007, UN 2008, Saygin and Patel 2010, IAI 2010)).